METHOD AND APPARATUS FOR INCREASING TRACK DENSITY BY ADAPTING WRITE FAULT GATE TO POSITION ERROR SIGNAL AS IT VARIES FROM ID TO OD

Priority is claimed from U.S. Provisional Patent Application Serial No. 60/246,341 filed November 7, 2000 entitled "Method to Achieve High Track Density by Adapting the Write Fault Gate to the Position Error Signal as it Varies Across the Stroke from ID to OD," which is incorporated by reference in its entirety.

FIELD OF THE INVENTION

The invention relates generally to data storage systems and, more particular, to a method for increasing track density of the magnetic storage medium associated with the data storage system.

BACKGROUND OF THE INVENTION

Fig. 1 is a block diagram illustrating a disk drive 100 in accordance with one embodiment of the present invention. As illustrated, the disk drive 100 is coupled to an external host computer 102 that uses the disk drive 100 as a mass storage device. It should be appreciated that the blocks illustrated in Fig. 1 are functional in nature and do not necessarily represent discrete hardware elements. For example, in one approach, two or more of the functional blocks within the disk drive 100 are implemented in software within a common digital processor.

With reference to Fig. 1, the disk drive 100 includes: at least one data storage disk 104, at least one transducer 106, an actuator arm assembly 108, a voice coil motor (VCM) 110, a read/write channel 112, an interface unit 120, a servo controller 122, and a disk drive controller 124. The disk drive 100 receives read and/or write requests from

the host computer 102 and carries out the requests by performing data transfers between the at least one disk 104 and the host 102. In a preferred embodiment, the disk drive 100 includes multiple disks 104 in a vertical stack arrangement with one transducer 106 for each operative disk surface. Typically, both surfaces of each disk 104 will be operative for storing user data and, therefore, the disk drive 100 will include two transducers 106 for each disk 104. Single sided disk arrangements can also be used. The interface unit 120 is operative for providing an interface between the disk drive 100 and the host computer 102. During read and write operations, the interface unit 120 provides a communications path, including data buffering functions, between the host computer 102 and the read/write channel 112. In addition, the interface unit 120 is operative for receiving commands and requests from the host 102 and directing them to the controller 124. The controller 124 then carries out the commands by appropriately controlling the elements within the disk drive 100.

The voice coil motor (VCM) 110 is operative for controllably positioning the transducers 106 with respect to their corresponding disk surfaces in response to a control signal (e.g., $i_{control}$) generated by the servo controller 122. Each transducer 106 is coupled to an integrated arm assembly 108 and move together under the influence of the VCM 110.

When performing a read or write operation, the controller 124 instructs the servo controller 122 to move one of the transducers 106 to a target track on a corresponding disk surface so that a data transfer can take place. The servo controller 122 then generates a control signal to move the identified transducer 106 from a present location to the indicated target track in a process known as a "seek" operation. Once the transducer 106 has arrived at the target track, the servo controller 122 enters a "track follow" mode during which the transducer 106 is maintained in a substantially centered position above the target track. The data transfer between the transducer 106 and the

target track occurs during this track follow mode.

The read/write channel 112 is operative for, among other things, performing the data transformations necessary to provide communication between the host computer 102 and the disk 104. For example, during a write operation, the read/write channel 112 converts digital data received from the host computer 102 into an analog write current for delivery to one of the transducers 106. During a read operation, the read/write channel 112 provides the data transformations necessary for converting an analog read signal received from one of the transducers 106 into a digital representation that can be recognized by the host computer 102. The read/write channel 112 is also operative for separating out servo information read by a transducer and for directing this servo information to the servo controller 122 for use in positioning the transducer.

A lookup table 126 in drive 100 is operative for storing a write fault gate track threshold value for the transducers on disk 104 in the disk drive 100. The write fault gate threshold values are used by the disk drive 100 during write operations to determine when a corresponding transducer has moved too far off-track to reliably write data to the track. When performing a write operation, the disk drive controller 124 first retrieves a write fault gate value from the lookup table 126 corresponding to the transducer 106 associated with the write operation. The controller 124 then allows data to be written to the target track only when the corresponding transducer 106 is within a positional window about the target track that is defined by the retrieved write fault gate threshold value. The disk drive controller 124 monitors the position of the transducer 106 during the write operation to determine whether it is within the threshold window. As long as the transducer 106 is positioned within the window, the write operation is allowed to continue. If the transducer 106 moves outside of the threshold window, the controller 124 suspends performance of the write operation until a future time. Typically, the controller 124 will resume writing data on a next pass of the corresponding portion of the

target track as long as the transducer 106 is properly positioned at that time. The controller 124 typically controls the writing of data to the target track using a write enable signal delivered to the read/write channel 112.

Figure 2 is a diagrammatic representation of a simplified top view of a disk 104 having a surface 242 which has been formatted to be used in conjunction with a conventional sectored servo system (also known as an embedded servo system), as will be understood by those skilled in the art. As illustrated in Figure 2, the disk 104 includes a plurality of concentric tracks 244a-244h for storing data on the disk's surface 242. Although Figure 2 only shows a relatively small number of tracks (i.e., 8) for ease of illustration, it should be appreciated that typically many thousands of tracks are included on the surface 242 of a disk 104.

Each track 244a-244h is divided into a plurality of data sectors 246 and a plurality of servo sectors 248. The servo sectors 248 in each track are radially aligned with servo sectors 248 in the other tracks, thereby forming servo wedges 250 which extend radially across the disk 104 (e.g., from the disk's inner diameter 252 to its outer diameter 254). The servo sectors 248 are used to position the transducer 106 associated with each disk 104 during operation of the disk drive 100. The data sectors 246 are used to store customer data, which is provided by the host computer 102.

Figure 3 illustrates a data storage disk 104 that is used to store digital data in a magnetic disk drive system. The disk 104 is substantially circular in shape and includes a center point 312 located in the center of the disk. The disk 104 also includes a plurality of tracks on a surface 314 of the disk 104 for storing the digital data. Ideally, each of the tracks is non-perturbed and ideally shares a common center 312 with the disk 104, such as ideal track 316 illustrated in Figure 3. Due to system imperfections, however, actual written tracks on the disk 104 can be perturbed as compared to ideal tracks, such as non-ideal track 318 in Figure 3. Consequently, transducer positioning is not as accurate on

track 318 as it would be on an ideal track. Perturbation can be the result of incorrectly written servo information relative to the ideal track centerline (RRO), and it can also be due to perturbation of the transducer itself relative to the ideal track centerline (NRRO).

As illustrated in Figure 3, the tracks on the disk 104 are each divided into a plurality of sectors 322. Each sector 322 is divided into a servo data portion and a user data portion (as described for Figure 2). The servo data portion includes, among other things, information for use by the disk drive in locating a transducer above a desired track of the disk 104. When a host computer requests that data be read from or written to a particular track/sector of the disk 104, the transducer must first be moved to the track and then must be positioned at a predetermined location with respect to the centerline of the track before data transfer can take place. The disk drive uses the information stored in the servo data portion of each sector to first locate the desired track and to then appropriately position the transducer with respect to the centerline of the desired track.

Figure 4 illustrates a typical servo pattern 424 stored within the servo portion 248 of a sector 322 for use in centering a transducer 106 on a desired track. The servo pattern 424 includes a plurality of servo bursts 426-432 that define the centerlines 434-438 of the tracks of the disk 104. The bursts 426-432 are divided into A bursts 426, 430 and B bursts 428, 432 that are each approximately a track-width wide and which alternate across the disk surface. The boundary between an A burst and an adjacent B burst (e.g., A burst 430 and B burst 428) defines the centerline (e.g., centerline 436) of a track on the disk. To center the transducer 106 using the A and B bursts, the transducer 106 is first moved to the desired track during a seek operation and, once there, is allowed to read the A and B bursts on the desired track. The signal magnitudes resulting from reading the A and B bursts are then combined (such as by subtracting the B burst magnitude from the A burst magnitude) to achieve an error signal, known as the position error signal (PES), which is indicative of the distance between the center of the transducer 106 and the

centerline of the desired track. The PES signal is used by the disk drive to change the position of the transducer 106 to one that is closer to the desired (centered) position. This centering process is repeated for each successive sector on the track until the requested read/write operation has been performed in the appropriate sector 322 of the disk 104. It should be appreciated that other schemes for storing servo information on the magnetic media (such as schemes using zones, constant linear density (CLD) recording, split data fields, and/or hybrid servo) can also be used in accordance with the present invention.

The A and B bursts 426-432, as well as other servo information, are written to the surface 314 of the disk 104 using a servo track writer (STW) after the disk 104 is assembled into the disk drive during the manufacturing process. It is these A and B bursts which define the location of the written tracks on the disk 104. That is, on a non-ideal track (such as track 318 of Figure 3) the A and B bursts are written such that the centerline of the track is not smooth, but rather is perturbed; this is the source of RRO. Further, a transducer can be made to position itself in a window positionally relative to the path of an ideal track by adding an appropriate offset value to the PES signal. Offset values, relative to the known RRO, may be used to modify the controller commands to the actuator and correct the RRO as the transducer follows the track.. RRO correction values are stored within the servo portions 248 of each sector 322 of the disk for use in positioning the transducer 106 in an approximation of ideal track path, such as 316, during track following operations.

As above mentioned, when a transducer moves off-track during a write operation, there is a chance that the transducer might inadvertently write data on or near an adjacent track, thus corrupting the data written on the adjacent track. In addition, the data that is written off-track by the transducer may be difficult or impossible to read during a subsequent read operation on the present track due to its off-track position. Thus, an off-track threshold value previously identified as a write fault gate is typically defined on a

disk drive that indicates an off-track transducer position beyond which the write operations will be suspended. If the transducer goes beyond the limits of the write fault gate threshold during a write operation, the write operation is suspended until the transducer again comes within the specified positional window about the target track.

In the prior art, the write fault gate threshold was determined during disk drive development based upon collected (worst case) off-track threshold data and estimates of transducer positioning error. Using a 3-sigma statistical distribution of the estimates of the transducer positioning error, a write fault gate threshold was set to an approximate value of value of 1.3 times the 3-sigma value of the position error at the worst case of the stroke, i.e., at the outer diameter (OD).

The single write fault gate threshold value thus derived was then used for all transducers within all drives in a production run. During disk drive tests, if the off track capability of the transducers in a particular drive were all within a specified range and the measured position error of the drive was within a corresponding range, the disk drive would pass certification limits. It would be assumed that the write fault gate threshold programmed into the drive would be sufficient to prevent adjacent track data corruption and unreadable off-track data. If the off track capability of a transducer was not within the specified range, the transducer would not be used in a disk drive. Similarly, if a particular disk drive displayed greater than a predetermined position error, the drive also would not be used. As can be appreciated, the greater the number of units that are left unused during the manufacturing process, the greater the overall manufacturing costs.

In an attempt to overcome the shortcomings of specifying a single off-track capability /write fault gate value for an entire production run of disk drives, unique off-track capability /write fault gate values were generated for individual disk drives during the manufacturing process. The write fault gate threshold values were determined based on the measured off track capability of each of the transducers actually within each drive

as well as a positioning error associated with that disk drive.

Because the write fault gate values were variable from drive to drive, transducers that were previously discarded as not falling within a predetermined off track capability range could be used as long as they occur in a drive having lower positioning errors. Similarly, drives having a large positioning error can be used if paired with transducers having superior off track capability. In this manner, manufacturing yields were increased without compromising disk drive performance.

Accordingly, in the recent prior art, a separate write fault gate threshold value was generated for each of the transducers within a manufactured disk drive. In one approach, a look up table is provided within the disk drive for storing the write fault gate values used by the drive. An appropriate value is retrieved from the look up table for each write operation performed by the disk drive. These write fault gate values are normally generated during the test procedure as part of the manufacturing process. Again, the prior art values are based on the position error at the worst case condition.

While the above described method of generating separate write fault gate values for each of the transducers in a disk drive permits matching transducers to a drive, enabling more drives to be certified for shipment, the write fault gate threshold values for the transducers are still limited by the minimum write fault gate threshold attributable to the position error at the worst case, i.e., at the outer diameter. Factors at the OD, such as air turbulence, radial distance from the inner diameter, etc., increase the threshold values of the write fault gates. At present, the write fault gate thresholds associated with a disk drive, even those providing write fault gate thresholds for each transducer, are a constant across the stroke of the actuator. However, tracks along the inner diameter, less subjected to the errors such as flutter, turbulence, vibration, etc. introduced into the disk along the outer diameter, may utilize smaller write fault gate thresholds but are still constrained to the same write fault gate thresholds as at the outer diameter tracks.

Accordingly, it would be advantageous to provide a method to accommodate the decrease in the write fault gate threshold requirements on the tracks as the transducer moves along the stroke toward the inner diameter of the platter, permitting a reduction in the track width and an attendant increase in track density.

SUMMARY OF THE INVENTION

The present invention is directed to a method for increasing the capacity of a disk drive by increasing the track density for each disk in the drive.

By measuring the changes in the position error as a transducer moves across the stroke between the outer diameter (OD) and the inner diameter (ID), values for the repeatable run out (RRO) and the non-repeatable run out(NRRO) may be obtained. Taking the root mean square (rms) of the RRO and the NRRO, a 3 sigma standard deviation position error signal (PES) curve may be derived.

The slope of the PES curve decreases across the stroke as the stroke moves from the OD towards the ID. The write fault gate thresholds for the tracks can be decreased in relation to the decrease of the slope, increasing the track density as the stroke approaches the ID, increasing the capacity of the drive.

Using the PES curve, the track-spacing may be varied with respect to the location of the track in relation to a position along the stroke by adjusting the write fault gate thresholds in relation to the slope of the PES curve.

By adjusting the write fault gate (WFG) threshold to the PES, we have a more uniform margin to encroachment failure across the entire stroke of the actuator; i.e., prior art had more margin at the ID. WFG thresholds provide the limit to how far a transducer can write off-track, so with equalized encroachment margin, tracks can be spaced closer together at the ID; this is the same thing as saying that the maximum WFG threshold will be made constant as a percent of track-spacing by increasing track-spacing density where

the PES is low. This provides a net gain in capacity through servo track-writing of more tracks on the disk where the PES is low.

This concept can be applied in many ways, three of which are: (1) A common PES curve between ID and OD can be established for a population of drives, and a variable track-spacing profile (curve) can be implemented for the whole population at the servo track-writer; (2) The PES can be measured by the servo track-writer for each drive and each surface at several points across the stroke, and from this data a unique track-spacing profile (curve) can be calculated for the worst PES on the worst transducer in the drive; (3) The PES can be measured by the servo track-writer for each drive and each surface at several points across the stroke, and from this data a unique track-spacing profile (curve) can be calculated for each transducer in the drive and a unique track-spacing profile (curve) can be written by the servo track-writer for each transducer and each surface in the drive.

The servo track-writing function, where we increase track-spacing density, can be performed by a conventional servo track-writer, self-servo track-writing, or by a variable track-spacing servo system. It will be obvious to those skilled in the art upon reading this disclosure that other implementations are possible.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a block diagram illustrating a disk drive in accordance with one embodiment of the present invention;

Figure 2 is a diagrammatic representation of a simplified top view of a disk having a surface which has been formatted to be used in conjunction with a conventional sectored servo system;

Figure 3 is a top view of a data storage disk illustrating a perturbed data track that can be compensated for in accordance with the present invention;

Figure 4 is a schematic diagram of a servo burst pattern that is used to position a transducer with respect to a track centerline;

Figure 5 is a flowchart illustrating a method for generating and storing write fault gate values during a disk drive manufacturing process in accordance with one embodiment of the present invention;

Figure 6 is a graph illustrating the signals utilized in determining the Position Error Signal used for deriving the write fault gate values for storage; and

Figure 7-11 are portions of a flowchart illustrating a detailed method for determining write fault gate values for a disk drive in accordance with one embodiment of the present invention.

DETAILED DESCRIPTION

While this invention is susceptible of embodiments in many different forms, there are shown in the drawings and will herein be described in detail, preferred embodiments of the invention with the understanding that the present disclosure is to be considered as an exemplification of the principles of the invention and is not intended to limit the broad aspects of the invention to the embodiments illustrated.

In conceiving of the present invention, the inventors have made a number of observations, some of which are listed below. Specifically, the inventors have recognized that track write width is a function of the write fault gate of that track with the write fault gate being a function of position error. Further, position error is a function of disk radius, decreasing as the radius approaches the inner diameter (ID) of the disk.

Additionally, the prior art uses steps of equal angle at the servo track writer which has the effect of increasing the track density at a rate approximately proportional to the inverse of the cosine of the skew angle of the head. As a result, it was noted that the magnetic track width decreases at a rate approximately proportional to the cosine of the skew angle of the head so that the effective write width shrinks as track density increases.

As is well known in the art, data storage capacities in magnetic storage devices are rapidly increasing. This increase in storage capacity is in large part due to the improvement in increased recording density on the magnetic media, allowing more data to be stored per unit area on the media. As the data density continues to increase, the number of tracks per inch (TPI) increases, resulting in a decreased track width for each track.

Referring now to Figure 5, there is shown a flowchart illustrating a method for generating and storing variable write fault gate threshold values during a disk drive manufacturing process in accordance with one embodiment of the present invention. A first disk drive is initially chosen for testing purposes (step 50). The disk drive is

typically chosen from a queue of assembled drives waiting to be tested. An off-track threshold value is then determined for each transducer within the selected disk drive. This is done by deriving a Position Error Signal (PES) across the stroke for each transducer in the selected drive, which signal is indicative of a variable off track threshold signal for that transducer (step 52). An average PES value with respect to a track can be determined, and referring also to Fig. 6, by first measuring the repeatable run out (RRO) signal 40 in Fig. 6, and the non-repeatable run out (NRRO) signal 42 in Fig. 6, for the transducer under test. The RRO signal is a measure of the repeatable off-track perturbations of the transducer as a consequence of reading servo bursts which are off-track of the ideal track centerline. The NRRO is a measure of the non-repeatable off-track perturbations of the transducer while track following; these perturbations are one component of the PES. The PES is equal to the root mean square (rms) value of the RRO and NRRO signals.

In referring to Figure 6, it is to be noted that the PES curve was developed using a disk rotational speed of 5400 r.p.m. Currently, rotation speeds up to 15,000 r.p.m. have also been used. The effect of higher rpm is more turbulence affecting the head and disk, such that the slope of the PES curve becomes steeper between the OD and the ID.

Once the PES is determined, a variable write fault gate threshold, i.e., the boundaries for each track along the stroke where the transducer can effectively operate without error, can be determined for the transducer under test (step 54) with the write fault gate being varied as a function of the PES signal along the stroke such that, and referring again to Fig. 6, the track PES and write fault gate threshold decease as the slope of the PES signal across the stroke from the OD to the ID decreases. Thus, based on the derived PES signal, at least one write fault gate threshold value, variable with respect to each track along the stroke, may be derived for each of the tracks within the disk drive and stored in a memory associated with the disk drive under test such as, (step 56). This

stored PES data may be used to increase track-spacing density where the PES is low. This operation is performed by the servo track-writer, or a self-servo write system.

In one aspect of the present invention, the lookup table 26 stores multiple write fault gate values, i.e., a separate, variable, value for each of the tracks on the disk drive 100 associated with a transducer 106. These write fault gate threshold values are specified as a variable function of radial position of the track on the corresponding disk surface. Thus, when data is being written to a target track on a disk surface, a write fault gate threshold value corresponding to that particular track is retrieved from the lookup table and used during the write operation. Again, the stored PES data may be used to increase track-spacing density where the PES is low. With the operation performed by the servo track-writer, or a self-servo write system.

A next disk drive is then selected for testing (step 58) and the method is repeated. The above-described method will preferably be repeated for every disk drive in the production run. This concept can be applied in many ways, three of which are: (1) A common PES curve between ID and OD can be established for a population of drives, and a variable track-spacing profile (curve) can be implemented for the whole population at the servo track-writer; (2) The PES can be measured by the servo track-writer for each drive and each surface at several points across the stroke, and from this data a unique track-spacing profile (curve) can be calculated for the worst PES on the worst transducer in the drive; (3) The PES can be measured by the servo track-writer for each drive and each surface at several points across the stroke, and from this data a unique track-spacing profile (curve) can be calculated for each transducer in the drive and a unique track-spacing profile (curve) can be written by the servo track-writer for each transducer and each surface in the drive.

Figs. 7-11 are portions of a flowchart illustrating a detailed method for determining variable write fault gate threshold values for a disk drive in accordance with

one embodiment of the present invention. The method is preferably performed during a disk drive testing procedure that is part of the disk drive manufacturing process. The method is further preferably performed after head optimization, channel optimization, and servo calibration procedures have been performed for the disk drive.

With reference to Fig. 7, at 'A', an initial transducer is first selected for testing within the disk drive (step 60). Using the selected transducer, a repeatable run out (RRO) error signal of the selected transducer is measured for each track as the transducer moves along the stroke from the outer diameter to the inner diameter of the disk drive (step 62). Referring also to Fig. 6, a typical RRO error signal measured across the stroke may be seen at 40. Next, a non-repeatable run out (NRRO) error signal is measured for the each track again as the transducer moves along the stroke from the outer diameter to the inner diameter and a typical NRRO signal measure may be seen in Fig. 6 as 42 (step 64).

From the RRO error signal 40 and the NRRO error signal 42, a position error signal (PES) 44 (see Figure 6) for the selected transducer may be derived. Referring now to Fig. 9, each of the stored RRO error signal and the NRRO error signal, 40, 42 respectively, are squared to obtain a product value for each. Next, the product values obtained for the RRO and NRRO error signals 40, 42 are summed (step 76). Taking the square root of the sum with the product values, a root mean square value which is the position error signal (PES) is derived (step 70A).

Utilizing the position error signal thus derived, and referring now to Fig. 8, step 68, a variable write fault gate threshold value for the tracks across the stroke may be determined. Referring again to Fig. 6, the slope along the derived PES signal may be seen at 44 to include an error signal for each track that varies in magnitude as the transducer traverses the stroke between the outer diameter and the inner diameter.

This variation in the PES magnitude provides the capability of varying the write fault gate, such as narrowing it as the PES varies from the outer to the inner diameter.

In so doing, track density on the disk drive may be increased by the servo track-writer as the PES varies across the stroke. This concept can be applied in many ways, among which are: (1) A common PES curve between ID and OD can be established for a population of drives, and a variable track-spacing profile (curve) can be implemented for the whole population at the servo track-writer; (2) The PES can be measured by the servo track-writer for each drive and each surface at several points across the stroke, and from this data a unique track-spacing profile (curve) can be calculated for the worst PES on the worst transducer in the drive; (3) The PES can be measured by the servo track-writer for each drive and each surface at several points across the stroke, and from this data a unique track-spacing profile (curve) can be calculated for each transducer in the drive and a unique track-spacing profile (curve) can be written by the servo track-writer for each transducer and each surface in the drive.

The variable write fault gate threshold for the tracks associated with the selected transducer may, as above described, then be stored in a memory associated with the selected transducer and associated disk drive. (Step 70) Next the method checks to see if this is the last transducer on the associated disk drive (Step 72). If it is the last transducer, and referring now to Fig. 10, step 80, the testing is ended as in step 82. However, if it is not the last disk drive, then the next disk drive is selected for testing as in step 84 returning back to Fig. 7.

If, in step 72, the "last transducer" check shows that this is not the last transducer on the associated disk drive, and referring now to Fig. 11, the method selects the next transducer for the associated disk drive to be tested as may be seen in step 86.

Although the above description is directed to an embodiment in which a unique track spacing profile is applied to every transducer and surface in the drive, other embodiments directed to applying a PES derived from a population of drives and one calculated to utilize the PES for the worst transducer in a drive are also considered within

the preview of this disclosure.

Referring again to Fig. 5, the average PES signal 44 for each track along the stroke is used to determine the write fault gate thresholds for such track. As the PES value varies in magnitude the write fault gate thresholds may be adjusted without the associated transducer exceeding the threshold limits.

Thus, as the magnitude of the write fault gate thresholds associated with the tracks narrow across the stroke as the transducer moves from the outer toward the inner diameter of the disk surface, track density increases as track width decreases.

Accordingly, track density increases toward the inner diameter (ID) at a rate proportional to the decrease in position error such that hard error recovery margin due to squeeze encroachment is equal across the stroke of the actuator.

Although the present invention has been described in conjunction with its preferred embodiments, it is to be understood that modifications and variations may be resorted to without departing from the spirit and scope of the invention as those skilled in the art readily understand. For example, the inventive principals can be used in conjunction with disk drives having a single write transducer. Further modification and variations are considered to be within the purview and scope of the invention and the appended claims.